STUDIES OF INTERACTIONS OF HIGH ENERGY PROTONS WITH COMPLEX NUCLEI

by

HELGE TYRÉN

APPELBERGS BOKTRYCKERI AB
UPPSALA 1958

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INAUGURAL DISSERTATION

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1. Introduction

The papers I–XV underlying this thesis are concerned with different scattering processes initiated by the bombardment of rather light nuclei with 185 MeV protons.

The essential features of the interaction of high energy nucleons with nuclei can be qualitatively understood with the help of some simple concepts.

One may firstly observe that the de Broglie-wavelength of 200 MeV protons is of the order of one tenth of the average distance of two nucleons in the nucleus. It is therefore possible to construct a well localized wave packet of the bombarding particle, introducing only a momentum uncertainty which is not large relative to the mean momentum. Consequently one may in many respects think of the bombarding proton as a classical particle penetrating the nucleus.

It is generally accepted that the nucleons in the nucleus are not strongly clustered. The interaction of the bombarding quasi-classical proton can then be considered in most cases as taking place successively with the individual nucleons of the nucleus [1]. From the known high-energy total nucleon-nucleon cross sections, one may calculate the mean free path of a nucleon in nuclear matter, correcting for the fact that the Pauli principle excludes certain collisions. The result roughly equals the radius of the oxygen nucleus [2]. Therefore, if high energy protons penetrate a light nucleus, relatively often no or only one collision occurs.

The influence of the nuclear nucleons with which no violent interaction takes place is not quite negligible. As a substitute for this influence a smooth attractive potential well may serve [3]. From elastic scattering the result has been obtained that the depth of this well decreases with increasing energy and amounts to about 15 MeV at 200 MeV bombarding energy [4]. In order to account for the finite mean free path, an imaginary part [5] of about the same size is added, and to give the observed spin dependence of the elastic scattering, a spin-orbit coupling of which the real part has the same sign as in the shell model is also introduced [6]. This so called "optical model" is able to reproduce the elastic scattering and the total cross section rather well, but an inelastic event is pictured as an absorbtion and no further information concerning these events can be obtained from the model.

For inelastic processes the optical model is nevertheless of importance because it determines the behaviour of the bombarding particle in the nuclear matter before and after the collisions with the individual nucleons in the nucleus. These collisions can be quantitatively treated by comparison with free nucleon-nucleon collisions [7].

In view of the developed picture we are now able to sketch the purpose of various experiments concerning the scattering of high energy protons on complex nuclei.

In elastic scattering, the nucleus stays in its ground state, no violent collision with a nuclear nucleon takes place, and therefore the interaction involves only the optical potential. Only information concerning the parameters of this potential can be obtained from these experiments. Most physical high-energy scattering measurements reported in the literature have been of this kind.

In the present work we have measured the polarization in the elastic scattering in some cases, but the main emphasis is laid on inelastic processes. Previous knowledge in this field was scanty because small groups of particles have to be selected out of large numbers, which is experimentally not easy to do at our energies.

In an inelastic event the state of the nucleus is changed. Although by these reactions information on the optical model and on nucleon-nucleon interactions can also be obtained, we have concentrated our attention on the investigation of the nuclear structure.

Of most interest are the cases in which only one collision of the bombarding proton takes place with a nucleon in the nucleus. If this nucleon stays in the nucleus, excited states corresponding to the single particle states in the shell model will be formed. Measurements concerning this type of events are considered in somewhat more detail in section 2.

If the nucleon struck receives such a large momentum that it is ejected from the nucleus one speaks of a "quasi-elastic" event. This expression does not refer to the elastic scattering of nucleons on nuclei, but to the scattering of nucleons on free nucleons, which evidently has a strong similarity with the quasi-elastic scattering.

It is not possible to separate those particles which have had a single collision from those particles which have had multiple collisions. Although these multiple events are numerically in the majority, in most cases they do not disturb the measurements on the singly scattered particles seriously. This is because the momenta of particles resulting from multiple collisions are smeared-out over a large region in momentum space and form only a smooth background in the measured spectra. Over this background the peaks resulting from single collisions are in general clearly visible, at least in the not too heavy nuclei. Section 3 is concerned with these experiments.

We have also been interested in the spin dependence of the elastic and inelastic scattering. These measurements on the polarization are reported in section 4.

Measurements in our energy region have many serious disadvantages against similar experiments at low energies. With increasing energy the size and cost of the apparatus to produce and analyse the particles increases and the absolute energy resolution and available intensities decreases strongly. Nevertheless some combined properties of a high energy nucleon, namely its penetrability through nuclear matter, its localizability and the high energy available, open a perhaps unique opportunity for the experimental investigation of certain aspects of nuclear structure. For example, measurements reported in section 3, giving direct experimental evidence for the inner shell structure of nuclei, show, that the energy required to remove a proton from the s-shell of a light nucleus amounts to about 30 MeV. Clearly the optimum energy for a bombarding nucleon to knock out such a proton from the nucleus is at least several times higher than this binding energy. It is indeed even considerably higher than the energy we had available.

2. Inelastic scattering with small energy losses

Measurements on the energy spectra of inelastically scattered 90 MeV protons resolving separate levels, have been reported by K. Strauch [8]. The only other experiment known to the author has recently been done in Harwell at 135 MeV [9]. Strauch employed a range technique, and at Harwell a total energy analysing crystal was used. Without going into details it may be remarked that an essential disadvantage of these techniques arises from the fact that every peak in the energy spectra has a considerable tail at the low energy side, mainly because of the nuclear collisions in absorbers or crystal. For this reason measurements are impossible at small scattering angles, where the elastic peak is several orders of magnitude larger than the inelastic peaks. This is especially serious because the interesting features of the angular distributions occur just at such small angles and could therefore not be found with these methods.

In this respect the magnetic analyser, built at this institute and used in the present experiments, is much more advantageous. For example, the smallest angle up to which the earlier mentioned measurements could be made in the light elements was 20 degrees, but measurements with the magnetic analyser have been made at 3.2 degrees. Our energy resolving power is about twice that of the other mentioned experiments.

In order to meet the strong requirements imposed by our measurements,

considerable work was put into the extraction and focussing of the proton beam [10].

The theory and general properties of the analyzer magnet are given in paper I. Paper II describes the experimental arrangement for its use in high energy proton analysis.

Measurements at at least two angles and in several cases complete angular distributions in nearly all elements with $Z < 31$ are reported in papers III–VIII.

As no theoretical treatment of these reactions was found in the literature, some ideas for the interpretation of the results have been developed in papers IX and X. It is possible to classify the strongly excited levels into four groups:

1) The single particle excitations by purely nuclear interaction, for which a large momentum transfer is necessary and which have therefore a forward dipped angular distribution.

2) Dipole excitations partly caused by Coulomb interaction with forward peaked angular distributions.

3) Excitations for which no large momentum transfer is necessary (for example spin flips) with forward peaked angular distributions.

4) Collective excitations which are forward dipped.

The qualitative agreement of the theory with experiment is good, although some features are not yet understood. Of particular interest are the dipole excitations at about 15–20 MeV, observed in all nuclei investigated except lithium, which are identical with the levels of the giant γ-resonance. Indeed, high energy proton scattering seems to be one of the most promising tools to investigate this type of levels.

More detailed calculations on our results concerning the 4.4 MeV level in carbon have been done or are being made by several authors [11].

The study of He^4, reported in paper IV is quite interesting. Improved results using a liquid helium target will be reported later. A low upper limit on the cross section for excitation of a bound level can be given and a virtual level is observed.

Some exploratory unpublished measurements have been made for the heavier elements. Probably because of the strong preponderance of multiple collisions in these larger nuclei, the sharp peaks are less abundant. The increasing elastic peak prohibits measurements at small angles.

3. Quasi-elastic scattering

As defined in the introduction, two protons emerge from a quasi-elastic event. In earlier experiments the energy distribution of one of the two coincident outcoming protons [12] and their angular correlations [13] have been studied.

We think that quasi-elastic scattering is able to give a wholly new type of information on nuclear structure. The theory and the experimental realization of this idea are the subject of the papers XI–XIII.

The essential point is a measurement of the energy carried away by each of the two coincident protons, which is accomplished by range analysis. To the extent that the collision is quasi-elastic, the difference between the sum of these energies and the incident energy, corrected for the recoil energy of the residual nucleus, gives the binding energy of the struck proton in the nucleus. Sharp groups which can be associated with the nuclear shell structure have been observed in the light elements. The results determine directly the spin-orbit splitting of the 1p-shell and the binding energy of the 1s-shell in the lightest nuclei. Only the spectrum of Be^9 might give some indication of an α-particle structure.

We hope to pursue this line further, both in experimental and theoretical directions. Energy and angular correlations, especially for the lightest elements, might give information on the nuclear wave functions, and, by comparison with a detailed calculation, on the distortion of the incoming and outgoing waves. The building up of the s- and d-shells in the elements between oxygen and calcium should be studied. By using higher bombarding energies one should be able to follow the inner shells further and to improve the results of paper XIII.

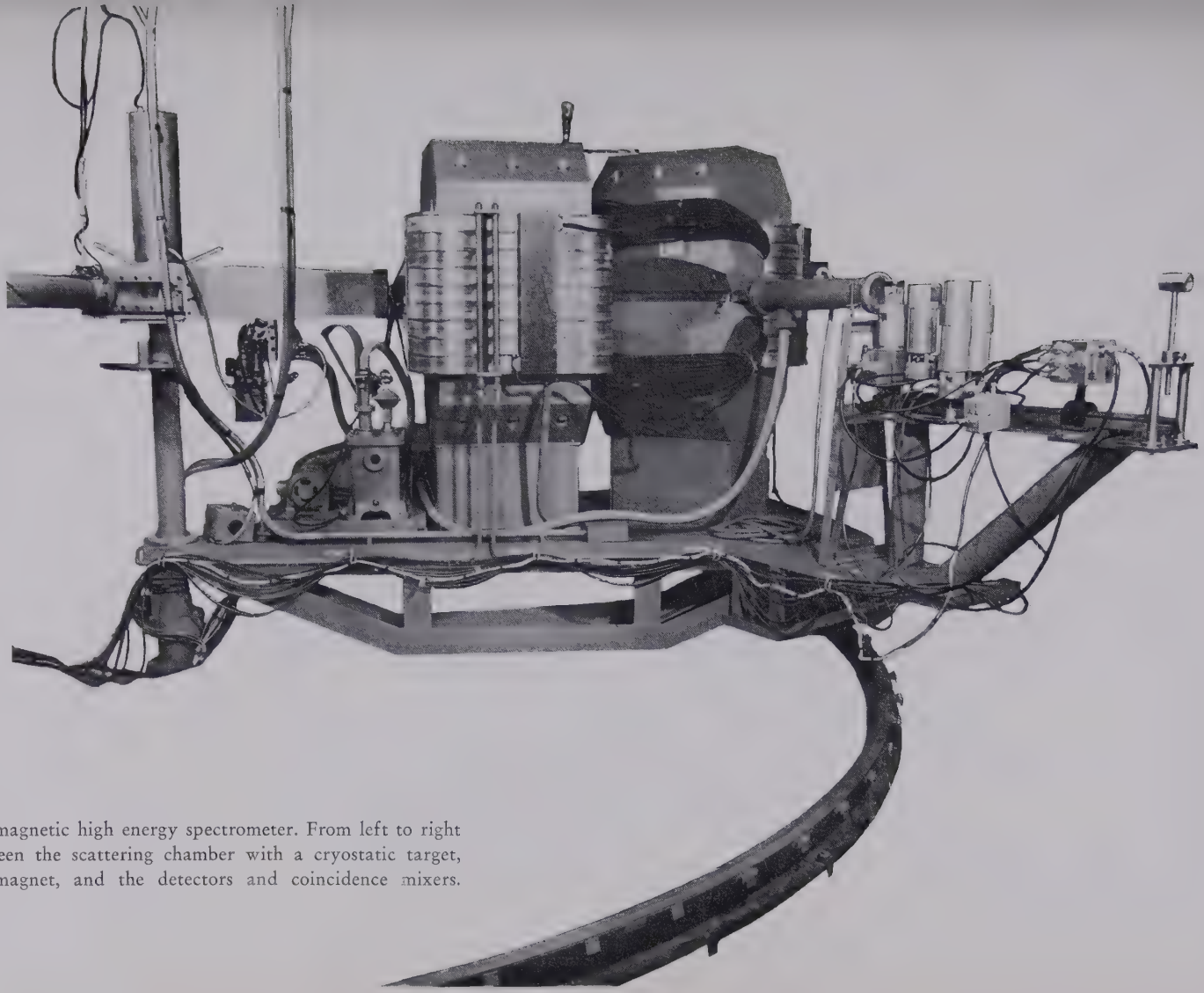
4. Polarization in elastic and inelastic scattering

Considering the spin dependence of high energy scattering cross sections, two quantities are of special importance: the polarization of the protons scattered by a nucleus out of an unpolarized beam and the asymmetry of the left and right hand scattering by nuclei bombarded with polarized protons.

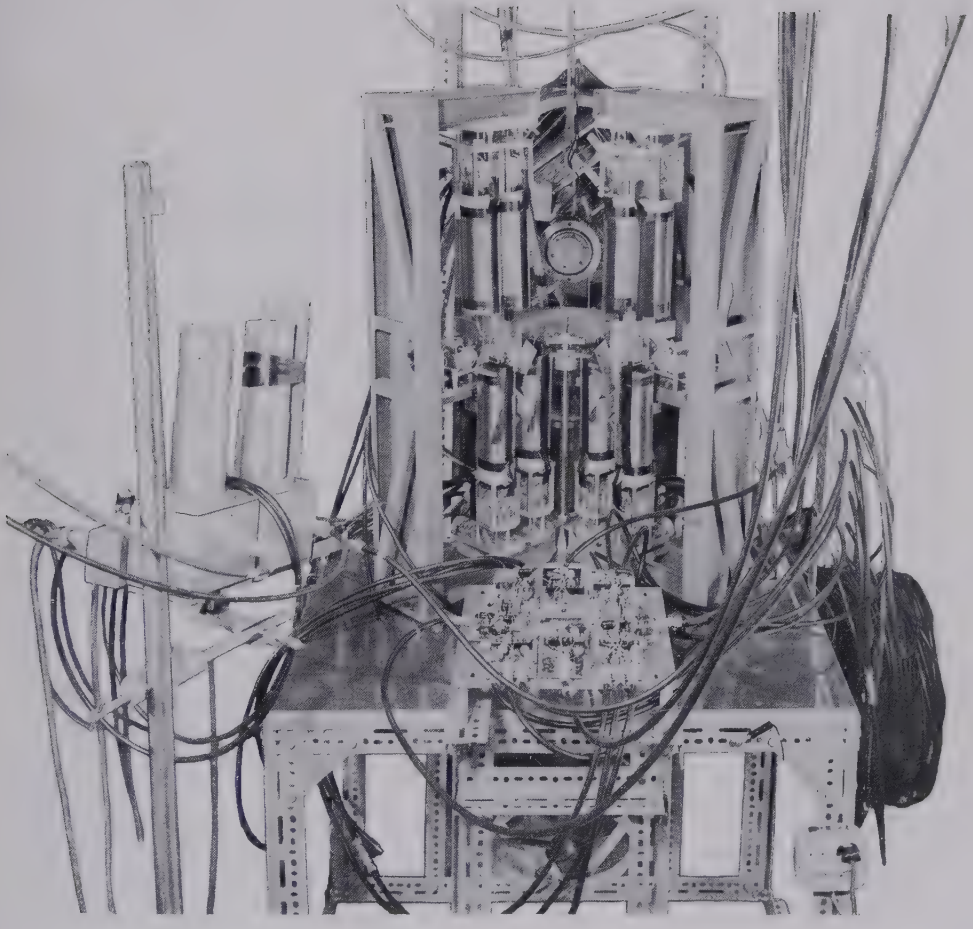
In the literature measurements on the asymmetries of roughly elastically scattered protons and on those exciting the first excited state of oxygen and calcium and some excited states in C^{12} have been reported [14]. No previous measurements on the polarization have been done.

In the papers XIV and XV a new technique is described for a measurement of the polarization of elastically and inelastically scattered protons. The essential instrument is a calibrated polarization analyser, which is positioned to receive the selected proton groups leaving the magnetic analyser.

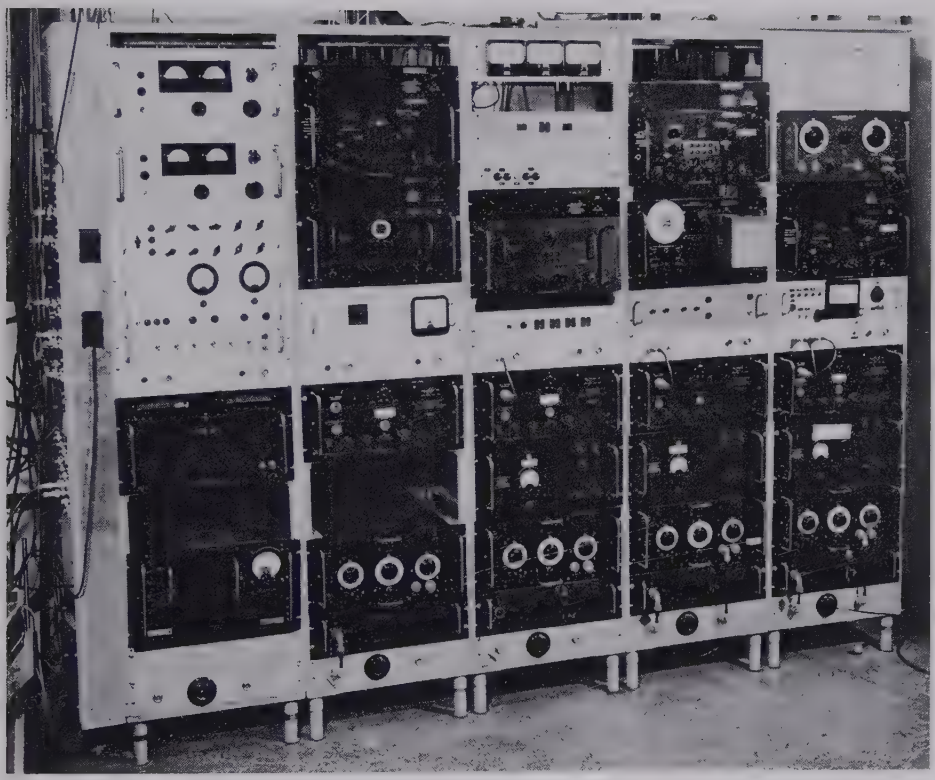
For the cases in which the asymmetry has been measured, there seems to exist a simple relation with the polarization. For elastic scattering this relation is theoretically expected; for inelastic scattering it is not quite understood. Clearly more theoretical work has to be done in order to get a clear understanding of the strong polarizations observed.



The magnetic high energy spectrometer. From left to right are seen the scattering chamber with a cryostatic target, the magnet, and the detectors and coincidence mixers.



The experimental set up for studies of quasi-elastic scattering. One sees the range telescopes, the compact array of coincidence mixers, and the monitor telescope.



The main electronics used for the high energy scattering experiments.

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